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CAUSES OF FLUCTUATIONS IN ABUNDANCE OF CONNECTICUT RIVER SHAD

By Reynold A. Fredin

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CAUSES OF FLUCTUATIONS IN ABUNDANCE OF CONNECTICUT RIVER SHAD

By REYNOLD A. FREDIN, *Fishery Research Biologist*

This study of fluctuations in abundance of the Atlantic shad (*Alosa sapidissima*) in the Connecticut River is part of a 6-year, coastwise study of the species sponsored by the Atlantic States Marine Fisheries Commission. The United States Fish and Wildlife Service, with the cooperation of the various State agencies along the Atlantic coast, has undertaken to determine the factors affecting the abundance of shad and to recommend measures for restoring the species to its former abundance.

The present commercial shad fishery on the Connecticut River is below Enfield Dam, in Connecticut, 60 miles from the mouth of the river, which rises in Quebec, Canada, and flows southward nearly 400 miles into Long Island Sound, at Saybrook, Conn. An angler's fishery is at the dam. Shad ascend the river as far as Holyoke, Mass., about 85 miles from its mouth, where a dam prevents further upstream movement. What effect the fishway now being constructed at the Holyoke Dam will have on future shad runs is not known.

Nearly all of the shad fishermen on the Connecticut River are gainfully employed in other occupations, but take leave from their jobs each spring during the shad season. After the legal season opens, a few fishermen start fishing at the mouth of the river to determine when the shad enter the river. Shortly after the first shad are taken, other fishermen at the mouth of the river begin operations and are in turn followed by those farther up the river. Fishing continues until the run dwindles. Since the fishermen take time off from their jobs for the sole purpose of fishing, and since the season is short, lasting from 6 to 8 weeks, the fishing effort remains fairly uniform throughout a given season. Logbooks, maintained by a few fishermen for a period of several years, show that once a fisherman commences fishing in a given season he fishes consistently until he stops for the year. Drift gill nets and haul seines are the types of commercial gear used throughout the fishery, except for one pound net located at the mouth of the river at the time of this study.

This paper presents information on some of the factors affecting the abundance of shad in the Connecticut River, such as water temperature, stream flow, pollution, and escapements, and on the basis of catch and effort data for a period of 17 years attempts to relate the fluctuations in abundance of the species to these factors.

Since accurate catch and effort records are prerequisite to determining fluctuations in abundance of shad or of any other species of fish taken commercially, and since a scientific interpretation of these fluctuations should precede any fishery-management recommendations, special recognition is due the Connecticut State Board of Fisheries and Game for having obtained statistics on the Connecticut River shad fishery for a number of years. I wish to thank Dr. R. P. Hunter, Lyle Thorpe, Douglas D. Moss, and other members of the Connecticut State Board of Fisheries and Game, for permission to use shad-fishery statistics and scale data from their official files; for assistance in conducting the field work; and for helpful suggestions pertinent to the investigation.

An expression of appreciation is due to members of the staff of the United States Fishery Laboratory, Beaufort, N. C., who helped in the field work and offered suggestions throughout this study; to Dr. D. B. DeLury, Ontario Research Foundation; Dr. R. J. Monroe, North Carolina State College; Dr. M. B. Schaefer, Inter-American Tropical Tuna Commission; and Elizabeth Vaughn for reviewing this paper; and to the shad fishermen of the Connecticut River without whose cooperation during tagging studies and in turning over their records for review, this work could not have been completed.

STATISTICS OF THE FISHERY, 1890–1951

Although commercial fishermen on the Connecticut River have reported their annual catches of shad to the State of Connecticut since 1890, and

the number of licenses issued for shad fishing has been recorded for each year from 1903 to 1930 and from 1932 to 1951 (table 1), this information is not sufficient to determine fluctuations in the abundance of shad over the past 50 years. License data are not a measure of actual fishing effort, since a record of a license issued for a unit of gear does not indicate what proportion of the season the gear was fished. In addition, many of the licensees used small scoop nets and set gill nets which are less than 100 feet long and anchored at one end to the river bank. These two types of gear are used only by part-time fishermen and are comparatively inefficient methods of taking shad.

TABLE 1.—*Shad catch and license data, Connecticut River, 1890–1951*

[Based on table prepared by Douglas D. Moss, Connecticut State Board of Fisheries and Game]

Year	Number of shad caught	Number of nets licensed	Lawful fishing days per week	Year	Number of shad caught	Number of nets licensed	Lawful fishing days per week
1890	34,318	----------	----------	1921	21,191	242	----------
1891	22,462	----------	----------	1922	13,821	118	7
1892	18,965	----------	----------	1923	13,350	103	4
1893	41,253	----------	----------	1924	25,316	90	4
1894	72,398	----------	----------	1925	43,365	92	5
1895	63,597	----------	----------	1926	37,177	96	5
1896	57,318	----------	----------	1927	34,321	94	5
1897	73,367	----------	----------	1928	56,191	80	5
1898	93,450	----------	----------	1929	91,597	99	5
1899	94,615	----------	----------	1930	66,136	87	5
1900	114,182	----------	----------	1931	18,506	----------	5
1901	124,927	----------	----------	1932	22,137	77	5
1902	107,208	----------	----------	1933	50,841	61	5
1903	176,085	130	----------	1934	115,361	52	5
1904	172,436	186	----------	1935	128,106	86	6
1905	120,358	203	----------	1936	109,752	81	6
1906	72,394	176	----------	1937	118,810	93	6
1907	38,880	156	----------	1938	127,283	102	6
1908	49,031	180	----------	1939	113,992	67	6
1909	34,972	150	----------	1940	95,703	57	6
1910	28,042	176	----------	1941	125,160	54	6
1911	27,640	134	----------	1942	110,520	54	6
1912	60,064	106	----------	1943	161,813	88	7
1913	52,053	112	----------	1944	214,086	99	7
1914	58,075	108	----------	1945	222,337	116	7
1915	41,377	155	----------	1946	301,556	199	6
1916	52,696	146	----------	1947	223,358	183	6
1917	64,766	170	----------	1948	175,250	167	5
1918	68,916	195	----------	1949	132,365	151	5
1919	82,303	156	----------	1950	77,090	135	5
1920	50,312	132	----------	1951	100,967	121	5

The Connecticut State Board of Fisheries and Game has in its files the annual reports submitted by individual fishermen for 1938 and for the years 1942 to 1951 which give the following information: Total number of shad caught during the fishing season, type of fishing gear used, number of days fished, and location fished. Although the individual reports are not available for the years 1939, 1940, and 1941, records of the total catches made by all fishermen and the number of commercial units (i. e., drift gill nets, seines, and pound nets) used in those years were obtained from the official files. Thus, for a period of 14 years, fishermen's reports provided catch and effort data for the Connecticut River shad fishery.

Fishing is not permitted every day during the time shad are in the river. Prior to each season, the Connecticut State Board of Fisheries and Game sets a number of rest days each week. The number of lawful fishing days a week for the years 1922 to 1951 is shown in table 1.

In totaling the catches reported by the individual fishermen, it was found that set gill nets and scoop nets combined took no more than 3 percent of the total catch in 1938 or in any season between 1942 and 1951. In this paper only the catches made by commercial types of fishing gear are used in the analyses.

A few words concerning the individual reports are in order. When a fisherman used two or more units of the same type of commercial gear, or two or more units of different types of commercial gear during a season, he did not report the catch made by each unit; but rather he gave a single figure for the catch by all units fished. No attempt has been made to differentiate the catches with respect to gear in such cases. From observations of the fishery and discussions with every fisherman on the river during the 1951 season, we learned that a fisherman who obtains licenses for two or more units of commercial gear hires crews of men to assist with the fishing. Once fishing operations begin in any season, it is economical to utilize the crews to the fullest extent, and all available licensed gear is used. Haul seines are generally fished by day and drift gill nets at night. Whenever a fisherman used two or more units of gear during a season and reported that he fished a certain number of days, I have assumed for purposes of this paper that he fished each unit of gear the number of days reported, unless otherwise stated in his report.

CATCH AND EFFORT DATA, 1938 AND 1942–51

Table 2, based on the annual reports of the fishermen filed with the State of Connecticut, shows the number of units of each type of gear in operation, the total number of days fished by each type of gear separately or in combination with other gear, and the total catch by each type of gear separately or in combination, for the years 1938 and 1942–51.

TABLE 2.—*Catch and effort data, by gear, for the Connecticut River shad fishery, 1938 and 1942–51*

Year	Drift gill net			Haul seine			Pound net			Drift gill net and haul seine combined					Drift gill net and pound net combined				
										Number of units		Net days fished			Number of units		Net days fished		
	Number of units	Net days fished	Number of shad taken	Number of units	Net days fished	Number of shad taken	Number of units	Net days fished	Number of shad taken	Drift gill net	Haul seine	Drift gill net	Haul seine	Number of shad taken	Drift gill net	Pound net	Drift gill net	Pound net	Number of shad taken
1938	28	1,095	63,134	12	405	46,866	1	45	1,856	1	1	45	45	13,500	------	------	------	------	------
1942	20	668	68,645	5	117	14,752	1	55	6,820	4	3	168	127	24,604	------	------	------	------	------
1943	28	1,196	111,178	6	170	13,989	1	60	7,700	2	2	115	115	26,489	------	------	------	------	------
1944	42	1,729	144,248	4	97	11,781	2	97	15,681	5	3	278	166	40,253	------	------	------	------	------
1945	57	2,518	147,448	4	69	4,000	2	125	10,875	8	5	488	303	54,563	------	------	------	------	------
1946	82	3,134	182,188	10	266	21,252	2	81	8,340	17	10	776	456	83,247	1	1	60	60	4,759
1947	80	2,595	110,079	15	461	38,797	1	31	440	20	11	870	478	64,049	1	1	60	60	5,625
1948	74	1,942	71,994	15	390	42,308	1	25	1,240	17	12	659	466	58,290	1	1	50	50	3,400
1949	61	1,715	48,510	21	510	44,725	1	15	304	15	10	499	333	32,974	1	1	48	47	4,082
1950	57	1,473	36,445	22	400	25,359	1	20	300	9	6	251	167	13,146	1	1	40	40	1,840
1951	55	1,438	56,448	16	362	32,734	------	------	--------	9	6	276	185	11,785	------	------	------	------	------
Average catch per net day fished	------	------	56.8	------	------	92.5	------	------	74.4	------	------	------	------	--------	------	------	------	------	--------
Relative efficiency of gear types to drift gill nets	------	------	1.0	------	------	1.6	------	------	1.3	------	------	------	------	--------	------	------	------	------	--------

When the catch per net-day fished is determined for each type of gear fished separately for each year shown in table 2, and the averages for the 11 years are obtained from the catch-per-net-day-fished values, it can be seen that haul seines took an average of 1.6 times as many fish per day's fishing as drift gill nets, and pound nets took an average of 1.3 times as many fish per day's fishing as drift gill nets. For the population of fish subject to capture by the types of gear used in the fishery, haul seines and pound nets are, respectively, 60 and 30 percent more efficient than gill nets. An adjustment is necessary before the catch per fishing-day effort can be determined, because the effort of a drift gill net fished 1 day is not comparable to that of a haul seine or a pound net fished 1 day. In this study a drift gill net is defined as a standard fishing unit. The fishing power of a standard fishing unit (s. f. u.) is the ability to capture in 1 day a certain fraction of the fish present in the Connecticut River; for a standard fishing unit (a drift gill net), the relative fishing power is taken as unity. The fishing power of the average haul seine is 1.6 times that of the average drift gill net, and it is therefore equal to 1.6 standard fishing units. A pound net is equivalent to 1.3 standard fishing units. The unit of effort is defined as a drift gill net which fishes one day; this will be termed a standard-fishing-unit day. Therefore, a haul seine which operates one day is equivalent to 1.6 standard fishing unit days, and a pound net which operates one day is equivalent to 1.3 standard-fishing-unit days.

The total number of standard-fishing-unit days a season is a measure of the total fishing effort expended and is given for 1938 and for the period 1942 to 1951 in table 3. The numbers of days fished by haul seines and pound nets have been converted to standard-fishing-unit days by using the conversion factors, 1.6 and 1.3.

TABLE 3.—*Fishing effort, by gear, in standard-fishing-unit days, 1938 and 1942–51*

Year	Drift gill net	Haul seine [1]	Pound net [2]	Drift gill and seine combination		Drift gill and pound combination		Total number of s. f. u. days
				Drift gill	Haul seine [1]	Drift gill	Pound net [2]	
1938	1,095	648	58	45	72	--------	--------	1,918
1942	668	187	72	168	203	--------	--------	1,298
1943	1,196	272	78	115	184	--------	--------	1,845
1944	1,729	155	126	278	266	--------	--------	2,554
1945	2,518	110	162	488	485	--------	--------	3,763
1946	3,134	426	105	776	730	60	78	5,309
1947	2,595	738	40	870	765	60	78	5,146
1948	1,942	624	32	659	746	50	65	4,118
1949	1,715	816	20	499	533	48	61	3,692
1950	1,473	640	26	251	267	40	52	2,749
1951	1,438	579	--------	276	296	--------	--------	2,589

[1] Based on conversion factor, 1.6.
[2] Based on conversion factor, 1.3.

DETERMINING FISHING EFFORT FOR 1935–37 AND 1939–41

Table 3 does not include data for the years 1939, 1940, and 1941, since the original reports were not

available, but the number of gill nets, haul seines, and pound nets in operation in those years, obtained from the official files of the State of Connecticut, was as follows:

Year	Gill net	Seine	Pound net	Total
1939	28	11	1	40
1940	20	10	1	31
1941	22	8	1	31

Although it is not known how many days were fished each year, the fishing effort for these 3 years can be estimated in the following way. First, the number of units of gear are converted into standard fishing units.

1939 ---------- 28+11 (1.6)+1 (1.3)=47 s. f. u.
1940 ---------- 20+10 (1.6)+1 (1.3)=37 s. f. u.
1941 ---------- 22+ 8 (1.6)+1 (1.3)=36 s. f. u.

The total fishing effort in a season is measured by the total number of standard-fishing-unit days. From table 3 the total standard-fishing-unit days for 1938 and 1942 are seen to be 1,918 and 1,298, respectively. The number of each type of gear in operation (listed in table 2), in these 2 years is as follows:

Year	Gill net	Seine	Pound net	Total
1938	29	13	1	43
1942	24	8	1	33

When these gear are converted into standard fishing units, the following is obtained:

1938 ---------- 29+13 (1.6)+1 (1.3)=51 s. f. u.
1942 ---------- 24+8 (1.6)+1 (1.3)=38 s. f. u.

The average number of days fished per standard fishing unit in 1938 and 1942 is equal to 1,918/51=37.6 and 1,298/38=34.2, respectively.

An examination of the daily records kept by a few fishermen who have fished since 1930 reveals that these fishermen fished fewer days in 1940 and 1941 than in 1938 and 1939; hence the average number of days fished per standard fishing unit in 1942 was used to estimate the total effort for 1940 and 1941. The average number of days fished per standard fishing unit in 1938 was used to estimate the effort for 1939. The estimated fishing effort in terms of standard-fishing-unit days for 1939, 1940, and 1941 is—

1939 ---------- 47 (37.6)=1,767 s. f. u. days
1940 ---------- 37 (34.2)=1,265 s. f. u. days
1941 ---------- 36 (34.2)=1,231 s. f. u. days

In 1938, 43 of the 102 nets registered were for commercial types of gear that were actually fished; 59 of the licenses were for scoop or set gill nets. The latter type of gear was permitted on the river for the first time in 1935, and in 1938 a total of 22 was in operation. Records are not available for the number of set gill nets licensed in each of the years 1935, 1936, or 1937, for which years 86, 81, and 93 nets were registered (table 1). Douglas D. Moss, aquatic biologist with the Connecticut State Board of Fisheries and Game, has estimated that approximately 25 scoop nets were licensed in each of the 3 years. Scoop nets were popular at that time as they provided many people with the opportunity to catch a few shad for a small outlay of money. The best estimate of the number of nets of commercial type that were actually fished in 1935, 1936, and 1937 appears to be 42 percent of the total number of nets registered in those years, or 36, 34, and 39 units, respectively.

Of the estimated number of units of gear in use in 1935, 1936, and 1937, the best estimate of the proportions of gill nets, haul seines, and pound nets is the proportion of each type that was fished in 1938. The estimated number of each type is as follows:

Year	Gill net	Seine	Pound net	Total
1935	24	11	1	36
1936	23	10	1	34
1937	26	12	1	39

Converting these figures into standard fishing units for each year, we obtain 43, 40, and 46. The 1938 value for the average number of days fished per standard fishing unit is used to estimate the total standard-fishing-unit days for 1935, 1936, and 1937, because the few fishermen who have fished consistently each year since 1930, and from whom records of daily catch and effort are available, fished approximately the same number of days in 1935, 1936, and 1937 as they fished in 1938. Estimates of the fishing effort, or total standard-fishing-unit days for 1935, 1936, and 1937 are 43 (37.6)=1,617; 40 (37.6)=1,504; and 46 (37.6)=1,730, respectively. No attempt is made to determine the fishing effort before 1935, because Mr. Moss has no estimate of the number of scoop nets that were licensed prior to that year.

FISHING EFFORT AND CATCH, 1935–51

The total fishing effort in terms of standard-fishing-unit days has been determined for each year for the period from 1935 to 1951, inclusive. The total catch for each of these years was obtained from reports submitted by the fishermen. For 1938 and the years 1942 to 1951, the reports on file in the office of the Connecticut State Board of Fisheries and Game supplied a record of the catches made by the commercial types of gear. For the years from 1935 to 1937 and 1939 to 1941, for which the individual reports were not on file, but for which records of total catches are available at the State Board of Fisheries and Game, an adjustment for the proportion of catch taken by noncommercial types of gear was made by subtracting 3 percent of the catch from the amount given in table 1. As pointed out earlier, in no one year for which all the individual reports are available was more than 3 percent of the total catch made by noncommercial types of gear. From 1935 to 1937 and from 1939 to 1941, the numbers of noncommercial types of gear operated were no greater than in the other years.

Table 4 shows the total catch, total fishing effort, and catch per unit of effort for each year from 1935 through 1951. The figures entered in this table represent the catch and effort data for the Connecticut River shad fishery for this period. I should like to remind the reader that the figures for fishing effort for 1935, 1936, and 1937 are estimates made from the information available. Figure 1 shows the curves for catch, fishing effort, and catch per unit of effort for the 17-year period.

TABLE 4.—*Total fishing effort and catch, and catch per unit of effort, Connecticut River shad fishery, 1935–51*

Year	Number of standard-fishing-unit days	Number of shad taken	Number of shad taken per s. f. u. day
1935	1,617	124,263	77
1936	1,504	106,459	71
1937	1,730	115,246	67
1938	1,918	125,356	65
1939	1,767	110,572	63
1940	1,265	92,832	73
1941	1,231	121,405	99
1942	1,298	114,821	88
1943	1,845	159,356	86
1944	2,554	211,963	83
1945	3,764	216,886	58
1946	5,309	299,786	56
1947	5,146	218,990	43
1948	4,118	177,232	43
1949	3,692	130,595	35
1950	2,749	77,090	28
1951	2,589	100,967	39

ESTIMATING THE SIZE OF THE BASE-YEAR SHAD RUN

Total catch and total effort have been determined for each year from 1935 to 1951. To estimate the population of shad in each of the 17 years, an estimate of total population for a base year was needed. During the 1951 shad fishing season, a tagging program was conducted to determine total population, escapement, and fishing rate. Tagging operations began at the mouth of the Connecticut River shortly after the first shad were taken by commercial fishermen there and were continued through most of the season. Two types of sampling gear were used for tagging. The first was a pound net located near the mouth of the river, the second an anchor gill net used in the mouth of the river. The mesh sizes of the tagging gear covered the range of mesh sizes of the nets used by the commercial fishermen. All fish taken in the gill net were tagged, and a high, nearly uniform proportion of the daily pound-net catch was tagged.

Petersen disk tags, three-eighths inch in diameter were inserted high on the backs of the fish, about one-fourth inch behind the anterior insertion of the dorsal fin. The possibility that the tags made the fish more susceptible to capture was considered. It was hypothesized that if the tags caused selectivity, a higher proportion of tagged fish would occur in the catch at the lower end of the fishery, where the shad were first susceptible to capture, than at the locations farther upstream. It developed that the proportion of tagged fish in the catches in the lower reaches of the river was no greater than in those made farther upstream. That tagging did not increase the fish's susceptibility to capture may be due to the fact that the shad is a deep-bodied fish and, in the Connecticut River, is generally gilled about the head or gills well forward of the point of insertion of the tag.

Biologists contacted each commercial fisherman once a week to pick up recovered tags and pay the 50-cent reward for each tag returned. A few tags were returned by mail. Of 633 Petersen disk tags used, 349 were recovered in the commercial fishery. In addition to the 349 tags actually returned by the fishermen, 10 tags were reported lost or misplaced. Thus the total number of tags accounted for by the commercial fishermen during the 1951 shad fishing season was 359. The proportion of returns of fish tagged from gill nets

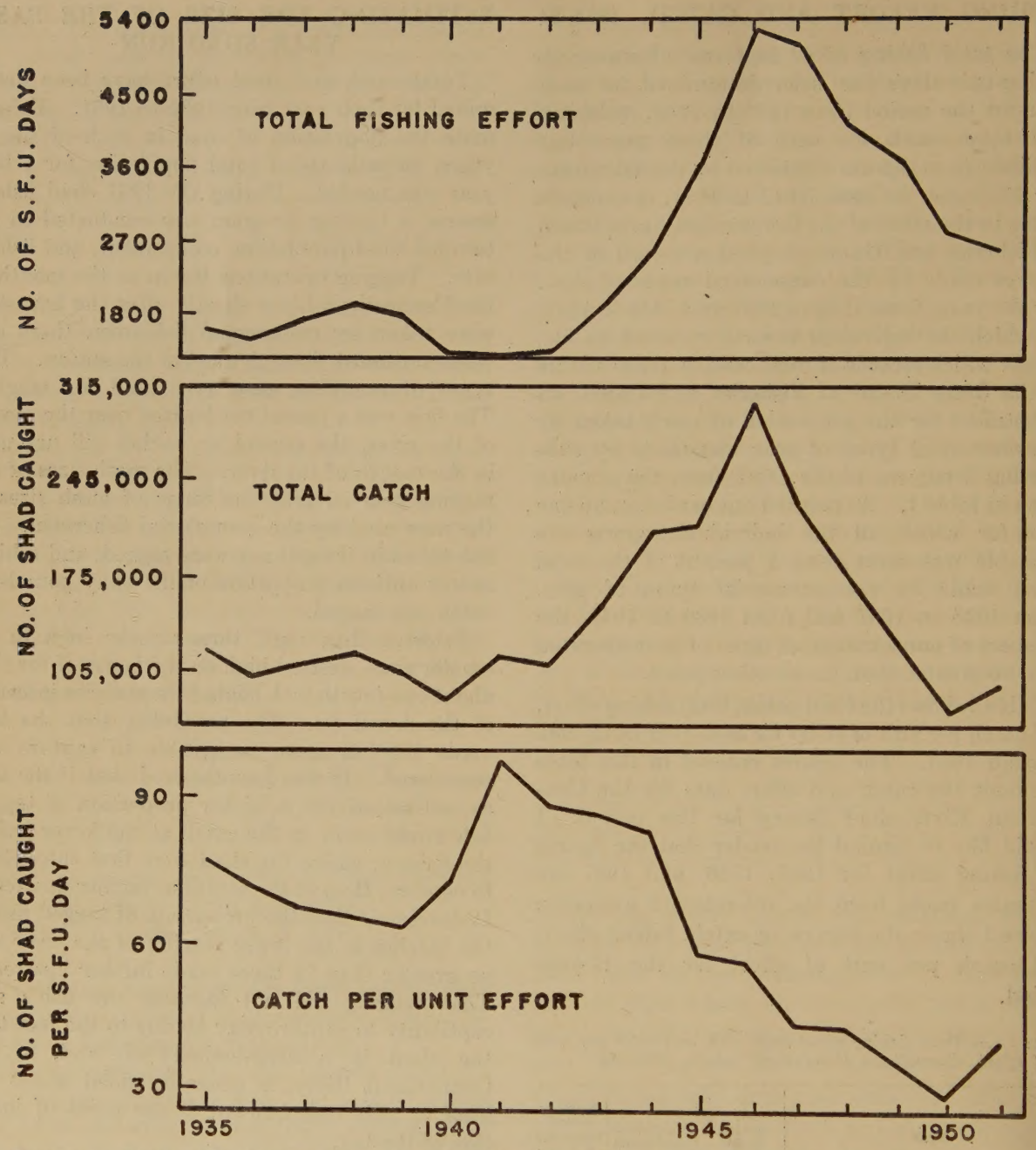

FIGURE 1.—Shad catch, fishing effort, and catch per unit of effort for the Connecticut River, 1935 through 1951

did not differ significantly from the proportion of returns of those tagged from pound nets.

Using the tagging data to estimate the fishing rate, where T equals the number of fish tagged, and T_c the number of tagged fish recaptured, the estimated fishing rate is T_c/T, or 359/633, which equals 56.7 percent. Assuming that the same proportion of untagged fish present in the river was removed by the fishery, where N equals the total population and C equals the catch, the best estimate of N is $\frac{C}{T_c/T}$. The total catch in 1951 was 100,967 shad; therefore, the best estimate of total population would be $\frac{100{,}967}{359/633}$, or $\hat{N}=178{,}072$ fish. Since the estimate of N depends upon T, T_c, and

C, the error in estimating N results from any error in these three quantities.

When C and T are without error, the error in $\hat{N}$ results from the sampling error in T_c; the variance of T_c takes on the form pqn; in this case, it is $(T_c/T)\ (1-T_c/T)\ (T)$, or $T_c(1-T_c/T)$. An approximation to the asymptotic variance of $\hat{N}=\hat{V}(\hat{N})$ is obtained from the expectation of $(d\hat{N})^2$ (Deming 1943) which gives

$$(d\hat{N})^2=\hat{V}(\hat{N})=\frac{T^2C^2(dT_c)^2}{T_c^4} \qquad (1)$$

where $(dT_c)^2$ is equal to $\hat{V}(T_c)$, or $T_c(1-T_c/T)$. For $T=633$, $T_c=359$, and $C=100{,}967$, the estimated variance of $\hat{N}$ is 38×10^6, and the standard deviation of $\hat{N}$ equals 6,175. The reader is referred to papers by Chapman (1948) and Schaefer (1951) for discussions of other formulae for estimating the variance of $\hat{N}$.

DETERMINING SIZES OF RUNS AND ESCAPEMENTS, 1935–50

The fishing power of a standard fishing unit has been defined as the ability of one unit of gear to capture a certain fraction of the fish present in 1 day's fishing. For the Connecticut River shad fishery this fraction will be designated by p and can be considered to be constant within a season and between seasons, provided: (1) There is no innovation in design or manipulation of gear to make it more, or less, efficient as a means of taking fish, (2) the fishing effort is uniform throughout the season, and (3) the migration pattern of shad in the river is similar each year. Daily catch and effort records kept since 1930 by a few fishermen and interviews with many fishermen indicate that the Connecticut River shad fishery meets these three requirements. Table 5 gives the number of days fished each week by a few fishermen who kept records of their fishing activities in past years. The sample is small but it does give an indication that the men fish consistently throughout a given season.

Considering the shad run as a whole and denoting its size by N, the number of fish removed in the first standard-fishing-unit day is pN. The number remaining after the first standard-fishing-unit day is qN, where $q=1-p$. The fish that escape in the first standard-fishing-unit day are susceptible to capture in the second standard-fishing-unit day; the number removed during the second standard-fishing-unit day is pqN. The number remaining after the second standard-fishing-unit day, and the numbers removed and remaining after succeeding standard-fishing-unit days are as follows:

TABLE 5.—*Number of days fished each week during fishing seasons, 1935–51, by sample of Connecticut River fishermen*

Year and fisherman	Number of days fished in week No.—								
	1	2	3	4	5	6	7	8	9
1935:									
Fisherman A	5	6	5	6	6	6	6	6	-----
Fisherman B	6	6	6	6	6	6	6	-----	-----
Fisherman C	6	6	6	6	6	6	6	6	-----
1936:									
Fisherman A	6	5	6	6	6	-----	-----	-----	-----
Fisherman B	6	6	6	6	6	6	6	6	-----
Fisherman C	5	6	6	6	6	6	6	6	-----
1937:									
Fisherman A	1	6	6	6	6	6	6	6	2
Fisherman B	6	6	6	6	6	6	6	6	-----
Fisherman C	5	6	6	6	6	6	6	6	-----
1938:									
Fisherman A	4	6	6	6	6	6	6	5	1
Fisherman B	6	6	6	6	6	6	6	6	-----
Fisherman C	4	6	6	6	6	6	6	6	4
1939:									
Fisherman A	3	6	6	6	6	6	6	5	4
Fisherman B	2	6	6	6	6	6	6	6	-----
Fisherman C	2	2	6	6	6	6	6	6	4
1940:									
Fisherman A	1	2	6	6	6	6	6	6	6
Fisherman B	1	2	6	6	6	6	6	6	-----
Fisherman C	1	2	6	5	6	6	6	6	3
1941:									
Fisherman A	6	6	6	6	6	-----	-----	-----	-----
Fisherman B	2	6	6	6	6	6	6	-----	-----
Fisherman C	6	6	6	6	6	6	5	6	6
1942:									
Fisherman A	6	6	6	6	6	6	6	6	5
Fisherman B	1	6	6	6	6	6	6	6	-----
Fisherman C	6	6	6	6	6	6	6	6	4
1943:									
Fisherman A	4	7	7	7	7	7	7	5	5
Fisherman B	1	7	7	7	7	7	7	7	-----
Fisherman C	5	6	5	6	7	7	7	6	6
1944:									
Fisherman A	3	7	7	6	7	7	5	-----	-----
Fisherman C	3	7	6	6	7	7	7	5	3
Fisherman D	3	4	7	7	7	7	7	7	-----
1945:									
Fisherman A	3	5	4	6	5	5	3	6	7
Fisherman C	5	4	6	5	7	6	5	6	7
Fisherman D	7	7	7	7	7	7	7	7	7
Fisherman E	7	7	7	7	7	7	7	7	-----
1946:									
Fisherman A	3	6	6	6	6	6	6	6	6
Fisherman C	5	6	6	6	6	6	6	5	5
Fisherman E	6	6	6	6	6	6	6	6	6
1947: Fisherman A	5	6	6	6	4	5	-----	-----	-----
1948: Fisherman A	5	5	5	5	5	5	1	-----	-----
1949: Fisherman A	1	5	5	5	5	5	-----	-----	-----
1950: Fisherman A	5	5	5	5	4	-----	-----	-----	-----
1951:									
Fisherman A	3	5	5	5	5	5	5	2	-----
Fisherman D	3	5	5	5	5	5	4	4	-----

	Number removed	*Number remaining*
1st s. f. u. day	pN	qN
2d s. f. u. day	pqN	q^2N
3d s. f. u. day	pq^2N	q^3N
4th s. f. u. day	pq^3N	q^4N
.	.	.
.	.	.
.	.	.
$n-1$ s. f. u. day	$pq^{n-2}N$	$q^{n-1}N$
nth s. f. u. day	$pq^{n-1}N$	q^nN

R. J. H. Beverton (unpublished manuscript) used the model shown above to estimate population parameters for the North Sea demersal fisheries. I have used this model to develop formulae for back-calculating estimates of fishing rates and total populations for an anadromous fishery.

After the nth standard-fishing-unit day, there remain q^nN fish. These fish represent the escapement. The problem is to determine q, then p, since $p=1-q$. From the 1951 tagging data, we have estimates of total population, N, and escapement, E. Table 4 shows that 2,589 standard-fishing-unit days of effort were expended in 1951. Proceeding,

$$\begin{gathered} q^nN=E \\ q^{2589}(178{,}072)=77{,}105 \\ q^{2589}=0.433 \end{gathered} \tag{2}$$

and $q=0.999675$; $p=1-q=0.000325$. In one standard-fishing-unit day 0.0325 percent of the fish remaining are removed. In 1951, for example, where the population is treated as a whole, i. e., $\hat{N}=178{,}072$ shad, in the first standard-fishing-unit day, 58 fish are removed and 178,014 remain; in the second standard-fishing-unit day, 58 fish are removed and 177,956 remain; in the 2,589th standard-fishing-unit day, 25 fish are removed and 77,105 remain.

Given that T_c/T is the fishing rate, then $(1-T_c/T)$ is the escapement rate. It can be seen that $q^n=(T-T_c)/T$. In this case, the sampling error in estimating q results from the sampling error in T_c. An approximation to the variance of q is obtained from the expectation of $(dq)^2$ (Deming 1943). This gives

$$dq=\frac{q(dT_c)}{n(T-T_c)} \tag{3}$$

$$(dq)^2=\hat{V}(q)=\frac{q^2(dT_c)^2}{n^2(T-T_c)^2}.$$

Since

$$(dT_c)^2=\hat{V}(T_c)=T_c(1-T_c/T),$$

$$\hat{V}(q)=\frac{q^2T_c}{n^2T(T-T_c)}$$

For $q=0.999675$, $T_c=359$, $T=633$, $n=2{,}589$, $\hat{V}(q)=3.08\times10^{-10}$, and the standard deviation of q equals 1.75×10^{-5}, or 0.0000175.

To determine the total catch, it is necessary to add the numbers of shad removed in each standard-fishing-unit day, as follows:

$$\begin{aligned} C&=pN+pqN+pq^2N+pq^3N+\ldots+pq^{n-1}N \\ &=pN(1+q+q^2+q^3+\ldots+q^{n-1}) \end{aligned} \tag{4}$$

The expression in the parentheses is the sum of the first n terms of a geometric progression where the first term takes on the value 1 and the common ratio is q. The sum can be expressed by the formula, $\frac{(1-q^n)}{(1-q)}$.

Then,

$$C=pN\frac{(1-q^n)}{(1-q)}, \tag{5}$$

and

$$N=\frac{C}{p\frac{(1-q^n)}{(1-q)}}. \tag{6}$$

For any previous year, where the total catch and the number of standard-fishing-unit days are known, we can determine the total population of shad in the river. For example, in 1950 when the total catch was 77,090 shad and total effort 2,749 standard-fishing-unit days, the total population is estimated as follows:

$$\begin{aligned} \hat{N}&=\frac{77{,}090}{0.000325\left[\frac{1-0.999675^{2749}}{1-0.999675}\right]} \\ &=\left[\frac{77{,}090}{0.588}\right]=131{,}105 \end{aligned} \tag{7}$$

The annual fishing rate for 1950 is estimated to be 58.8 percent, and the total escapement is 54,015 shad.

Formula 6 has been used to estimate the total population, annual fishing rate, and escapement for each year that catch and effort data are available. These estimates are given in table 6 for the period from 1935 to 1951.

Some workers may question the validity of treating the river run of an anadromous species as a whole, since all the fish do not enter the river simultaneously. However, if the 1951 run were treated as a number of groups entering the river throughout the season and the number of fish in each group were known, it would be possible to determine p provided catch figures for each group were available and fishing effort were uniform for each group. With uniform fishing effort, p would remain constant throughout the season. Further, this p value could be used to determine total populations and escapements for other years where we have (1) the same number of groups

TABLE 6.—*Estimated total population, annual fishing rate, and escapement of shad in the Connecticut River shad fishery, 1935–51*

Year	Number of s. f. u. days	Number of shad taken	Annual fishing rate	Total population ($\hat{N}$)	Escapement ($\hat{E}$)
			Percent		
1935	1,617	124,263	40.6	306,066	181,803
1936	1,504	106,459	38.4	277,237	170,778
1937	1,730	115,246	42.7	269,897	154,651
1938	1,918	125,356	46.1	271,922	146,566
1939	1,767	110,572	43.4	254,774	144,202
1940	1,265	92,832	33.5	277,110	184,278
1941	1,231	121,405	32.8	370,137	248,732
1942	1,298	114,821	34.2	335,734	220,913
1943	1,845	159,356	44.8	355,705	196,349
1944	2,554	211,963	56.1	377,831	165,868
1945	3,764	216,886	70.3	308,515	91,629
1946	5,309	299,786	81.9	366,039	66,253
1947	5,146	218,990	81.0	270,358	51,368
1948	4,118	177,232	73.5	241,132	63,900
1949	3,692	130,595	69.6	187,636	57,041
1950	2,749	77,090	58.8	131,105	54,015
1951	2,589	100,967	56.7	178,072	77,105

entering the river, (2) uniform fishing effort throughout the season, and (3) catch statistics by groups.

Although the runs may vary from year to year with regard to the length of time they last, the number of groups in the runs can be assumed to be uniform each year. Certain river conditions may speed up or retard the passage of the entire run through the fishery, but such a situation is the sum of the effects of the river conditions on the individual groups. A large run may take longer to pass through the fishery, but in this case the individual groups can be considered to be larger in size and require a longer period of time to move up the river. Because of the nature of the Connecticut River shad fishery, the fishing effort can be considered to be uniform throughout a given season. Catch records cannot show the catch by groups because of mixing of groups within the river; therefore, the number of fish in each group cannot be determined. For this reason, I have treated the runs as a unit. The results obtained by treating the runs either as a whole or in parts are identical. The same estimates of total population and escapement prevail.

FACTORS AFFECTING THE SIZE OF CONNECTICUT RIVER SHAD RUNS, 1940–51

FISHING

The total population of shad in any year includes fish which are susceptible to capture for the first time and fish which, although they were susceptible to capture the previous season, have managed to escape the fishery and return to the river to spawn again. The expressions, "catchable recruits" and "repeaters," will be applied to these two groups of fish.

The ages of nearly 2,000 fish taken in the 1951 commercial catch were determined by a scale-reading technique developed by J. P. Cating (1953). Of the catchable recruits, 90 percent were 4- or 5-year-old fish that were spawning for the first time. The remaining 10 percent were shad returning to the river for the first time as 3-, 6-, and 7-year-old fish and a few 4-year-old males that had spawned once, but, as will be pointed out later, were too small to be caught by the commercial gear the first time they spawned.

The three major components of the total population are 4-year-old catchable recruits, 5-year-old catchable recruits, and repeaters. The relationships among total population in year i, escapement or brood stock size in year $i-5$, escapement or brood stock size in year $i-4$, and escapement in year $i-1$, can be evaluated by means of multiple regression. Further, the amount of information furnished in advance by the escapement data can be determined. The following data are incorporated in table 7: Total population for each year from 1940 to 1951 with the corresponding escapements 1, 4, and 5 years earlier; predicted total populations, $\hat{Y}$; the deviations from regression, $Y-\hat{Y}$; the regression equation; the partial correlation coefficients; an analysis of variance for multiple regression; and the multiple correlation coefficient.

The R value obtained is significant at the 1-percent level; it can be inferred that 83 percent of the variation in total population can be accounted for by changes in the escapements from the fishery. Of the three partial correlation coefficients shown in table 7, $r_{YX_3 \cdot X_1X_2}$ is highly significant, and $r_{YX_1 \cdot X_2X_3}$ approaches significance; on the other hand $r_{YX_2 \cdot X_1X_3}$, although positive, is small. The low value of $r_{YX_2 \cdot X_1X_3}$ may be explained by the possibility that the 4-year-old catchable recruits did not contribute as greatly to the runs in years prior to 1951 as they did in 1951 when the major components of the runs were determined from commercial scale samples. Further scale collections from the commercial catch will yield more information on this.

TABLE 7.—*Multiple regression of estimated population in year i (Y) on escapement in year $i-5$ (X_1), escapement in year $i-4$ (X_2), and escapement in year $i-1$ (X_3), with population expected from regression ($\hat{Y}$) and deviation from expected population ($Y-\hat{Y}$), in thousands of fish*

Year (i)	X_1 E_{i-5}	X_2 E_{i-4}	X_3 E_{i-1}	Y $\hat{N}_i$	$\hat{Y}$	$Y-\hat{Y}$
1940	182	171	144	277	310	−33
1941	171	155	184	370	331	39
1942	155	147	249	336	371	−35
1943	147	144	221	356	343	13
1944	144	184	196	378	335	43
1945	184	249	166	309	353	−44
1946	249	221	92	366	320	46
1947	221	196	66	270	277	−7
1948	196	166	51	241	243	−2
1949	166	92	64	188	214	−26
1950	92	66	57	131	162	−31
1951	66	51	54	178	141	37

$$\hat{Y}=48.10655+0.52543X_1+0.31298X_2+0.78338X_3$$

$$r_{YX_1 \cdot X_2X_3}=0.413,\ P\sim 0.25$$

$$r_{YX_2 \cdot X_1X_3}=0.253,\ P\sim 0.48$$

$$r_{YX_3 \cdot X_1X_2}=0.818,\ P<0.01$$

ANALYSIS OF VARIANCE

Source:	*Degrees of freedom*	*Sum of squares*	*Mean square*
Total	12	1,040,752	------
Mean	1	963,333	------
Regression	3	64,490	21,497
Error	8	12,929	1,616

$$F=\frac{21,497}{1,616}=13.303,\ P<0.01$$

$$R^2=0.833;\ R=0.912,\ P<0.01$$

ENVIRONMENTAL CHANGES

The deviations from regression in table 7 reflect the effects of other factors on the total population of shad. Water temperatures, stream flow, and dissolved oxygen data have been carefully studied, but none of these variables exhibits changes or trends that would account for the changes in total population or the deviations from the predicted populations. However, until representative samples of scales are taken from the commercial fishery for a series of years and the year-class sizes are estimated, it is not possible to determine fully the effects of these variables during the spawning season on the size of the year class.

EXTRANEOUS MORTALITY

One factor which may affect the deviations from regression is the mortality which occurs among the adult shad between fishing seasons. This mortality could be from natural causes during or following spawning in the river, natural causes at sea, or from fishing outside the river. The 1951 tagging experiment and similar studies by Hollis (unpublished manuscript), and Westman and Bevelander (correspondence with Dr. Westman), show that Connecticut River shad are taken by fishermen off the coast of Maine, in Sandy Hook, Raritan and Lower New York Bays, off Long Island, and along the New Jersey coast.

The mortality that occurs among the adult shad between fishing seasons will be referred to as extraneous mortality in this paper. If scale samples representative of the commercial catch with respect to gear and sex were available for a number of years, the extraneous mortality rates could be easily estimated. Since most of the scale samples have been collected from the highly selective gill-net fishery in the past, it is necessary to use scale data from the sport fishery at Enfield Dam.

The Connecticut State Board of Fisheries and Game has collected scale samples at the Enfield Dam sport fishery each year since 1944. These samples represent from 10 to 33 percent of the anglers' catches and are taken in the same manner each year. Before these scale samples can be used for mortality determinations, the assumption must be made that the fish caught at Enfield Dam are representative of the fish escaping the commercial fishery. An examination of the lengths and ages of fish taken by anglers at the dam reveals proportionately more small 3-year-old males in the sport-fishery samples than in the commercial-fishery samples. The apparent disproportionate number of small males may be due to the fact that some of these fish are too small to be caught by commercial gear, or may result from a lack of samples from the haul-seine fishery which generally takes more small male shad than does the gill-net fishery. Only when more representative samples from the commercial catch are obtained can the discrepancy be explained. In the meantime, I do not believe one can safely assume that the small males in the sport-fishery samples are representative of the fish escaping the commercial fishery each year.

Even though the relative abundance of all other fish is assumed to be the same in the Enfield Dam samples as in the group of fish escaping the fishery, the effects of disproportionate numbers of 3-year-old males in the Enfield samples can cause serious errors in mortality-rate determinations. For this reason, in estimating mortality rates I have selected 2 successive years when the 3-year-old males were in the same proportionate abundance in the sport-fishery samples.

In 1946, the proportion of 3-year-old males the sample from Enfield Dam was 21.9 percent; the proportion in 1947 was 22.6 percent. hese are the only 2 successive years in which e proportionate abundance of 3-year-old males the Enfield Dam sample was similar. In 1946, e 6-year-old class predominated in the Enfield am samples. The total and extraneous-ortality rates among this group of fish for 1 ar will be determined.

here

P_6 =the proportion of 6-year-old fish in the sample from Enfield Dam in 1946,

P_7 =the proportion of 7-year-old fish in the sample in 1947,

E_{1946}=the estimated total escapement in 1946,

E_{1947}=the estimated total escapement in 1947,

en,

$n_6=P_6E_{1946}$=the number of 6-year-old fish that escaped the fishery in 1946.

$n_7=P_7E_{1947}$=the number of 7-year-old fish that escaped the fishery in 1947,

d

$\frac{n_6-n_7}{n_6}$=the total mortality rate among 6-year-old fish for 1 year.

During the course of a year, the 6-year-old ad are subject to mortalities from two sources: traneous mortality and fishing mortality in the ver. Extraneous mortality occurs prior to the llowing season's fishing mortality in the river; e number of deaths by extraneous causes is sumed to be negligible during the fishing season. here M_x is the extraneous mortality rate and M_f is the river fishing mortality rate, the total mber of deaths among the 1946 6-year-old oup is:

$$M_xn_6+M_f(n_6-M_xn_6)=n_6-n_7; \qquad (8)$$

rther,

$$M_x=\left[\frac{n_6-n_7}{n_6}-M_f\right]\div(1-M_f). \qquad (9)$$

The total and extraneous mortality rates of the year-old shad escaping the fishery in 1946 are timated as follows:

E_{1946}=66,253.

E_{1947}=51,368.

$f_{,1947}$=0.810.

K_1=the number of fish sampled at Enfield Dam in 1946=1,183.

K_2=the number of fish sampled at Enfield Dam in 1947=1,344.

P_6=proportion of 6-year-old fish among K_1 fish $=\frac{273}{1,183}=0.231$.

P_7=proportion of 7-year-old fish among K_2 fish $=\frac{48}{1,344}=0.036$.

$n_6=P_6E_{1946}=0.231(66,253)=15,304$.

$n_7=P_7E_{1947}=0.036(51,368)=1,849$.

$\frac{n_6-n_7}{n_6}=\frac{15,304-1,849}{15,304}=0.879$=the total mortality rate.

$M_x=\frac{.879-.810}{1-.810}=0.363$.

An approximation to the variance of M_x is obtained from the expectation of $(dM_x)^2$ (Deming 1943):

$$(dM_x)^2=\hat{V}(M_x)=\left[\frac{\frac{P_6^2P_7(1-P_7)}{K_2}+\frac{P_7^2P_6(1-P_6)}{K_1}}{P_6^4}\right]\left[\frac{E_{1947}}{E_{1946}(1-M_f)}\right]^2 \qquad (10)$$

For the case presented, $(\hat{V}M_x)=0.009195$; the standard deviation is approximately 0.096.

The number of 6-year-old shad that escaped from the fishery in 1946 and died from extraneous causes before returning to the river in 1947 is estimated to be 0.363 (15,304), or 5,555 fish. The commercial fishery in the river removed 0.81 (15,098–5,345), or 7,897 fish of this age class. Thus, of the total of 13,452 deaths, about 40 percent occurred outside the Connecticut River shad fishery, and the effect of the extraneous mortality on the 6-year-old group of shad was nearly as great as the river-fishing mortality. Extent of fluctuation in the extraneous-mortality rate from year to year is not known, but if a standard sampling technique is followed in the collection of scales from the commercial catch, and samples are taken each year for a number of years, the extraneous-mortality rate can be estimated each year and changes in it determined.

It was pointed out earlier that tagging studies have shown that Connecticut River shad are

taken by fishermen off the coast of Maine, in Sandy Hook, Raritan, and Lower New York Bays, off Long Island, and along the New Jersey coast. One of the causes of extraneous mortality could be fishing in these areas.

From the New Jersey Division of Fish and Game and the New York Conservation Department, the records of the catches of shad (in pounds) by pound-net fisheries off the New Jersey coast, in Sandy Hook, Raritan, and Lower New York Bays, and off Long Island have been obtained for the years 1946 to 1950, as follows:

Year	New Jersey coast, Sandy Hook, and Raritan Bay	Lower New York Bay	Long Island	All areas combined
1946	500,000	176,000	120,000	796,000
1947	303,000	253,000	36,000	592,000
1948	573,000	224,000	48,000	845,000
1949	411,000	95,000	55,000	561,000
1950	480,000	204,000	(1)	(2)

[1] Not available.
[2] Incomplete.

The number of pound nets in operation by New Jersey fishermen increased each year from 144 in 1946 to 180 in 1950. Dr. James Westman, Rutgers University, has informed me that before 1945 the Long Island pound nets were usually not put in operation early enough in the spring to fish for shad; but since 1945 the Long Island pound nets have fished for shad. It is interesting that negative deviations from regression occur in 1947, 1948, 1949, and 1950 in table 7. The negative deviations from regression reflect an adverse condition such as an increased extraneous mortality which might be related to an increase in pound-net effort.

The relation between pound-net catches and deviations from the expected populations in the Connecticut River cannot be fully evaluated at this time because the extent to which Connecticut River shad contribute to these pound-net catches is not known. Additional tagging studies conducted in the areas where pound nets are fished would enable us to determine the effect of this fishing on the Connecticut River shad runs. The causes of the extraneous-mortality rate must be taken into consideration in a management program to restore the Connecticut River shad population to the level of abundance which it held in the early 1940's.

CONCLUSIONS AND RECOMMENDATIONS

The Connecticut River shad reached a peak of abundance in the middle 1940's, the runs becoming smaller after 1946. According to analyses of population and escapement data, over 80 percent of the fluctuations in the size of the runs can be attributed to changes in the size of the escapement from the fishery. For a given number of shad entering the river, the proportion of fish escaping the fishery depends upon the fishing rate. The fishing rate not only was higher from 1944 to 1951 than it was from 1935 to 1943 (table 6), but the average size of the runs since 1944 has been smaller. The conclusion is that the decline in the abundance of shad since the middle 1940's can be attributed, chiefly, to overfishing in the river. The extraneous-mortality rate might also affect the size of the run entering the river. If further studies show that the extraneous-mortality rate is a function of ocean pound-net fishing, the problem of restoring the shad runs to their former level of abundance broadens in scope; the pound-net fisheries, as well as the river fishery, would have to be managed. However, one inference from analysis of the data is clear: when the escapement totals are increased, the size of the runs in later years may be expected to increase.

As a result of the studies conducted in the Connecticut River, the following conclusions have been reached relative to the management of the shad fishery: The size of the shad run can be predicted one season in advance within desired limits of confidence, fishing effort and fishing rate can be estimated prior to the beginning of the season; hence the fishing effort should be adjusted to permit escapement of a predetermined number of shad.

Until additional information is obtained on the extraneous-mortality rate, the river-fishing effort should be maintained at a level that will permit adequate spawning escapements to build up the Connecticut River shad run. For the present, the river-fishing effort should not exceed the 2,589 standard-fishing-unit days of effort expended in 1951.

The most important contributions that can be made toward the management of the river fishery are the continued collection of scale samples and the maintenance of catch and effort records from the commercial fishery. The scale samples should

be representative of the fish taken with respect to gear and sex. Accurate fishery statistics, that is, catch and effort data, should be collected for the pound-net fisheries along the New Jersey coast, in Sandy Hook and Lower New York Bays, and off Long Island. Tagging studies should be conducted from the pound-net fisheries of New York and New Jersey to determine the proportion and number of Connecticut River shad that are taken by these fisheries.

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